TITLE OF THE INVENTION

Self-Centering Energy Dissipative Brace Apparatus with Tensioning Elements

FIELD OF THE INVENTION

[0001] The present invention generally relates to an energy dissipative brace apparatus with self-centering properties. More specifically, the present invention is concerned with a brace apparatus for installation in structures which may be subjected to extreme loading conditions.

BACKGROUND OF THE INVENTION

[0002] Although the design of structures under normal loading conditions aims at meeting serviceability and ultimate strength requirements by providing strength, stiffness and stability, it has been recognized recently that to effectively and safely resist extreme loading conditions such as earthquakes and blast loads, a fundamentally different approach must be used. It is economically unfeasible as well as being potentially unsafe to design structures for linear elastic response under such loading conditions, especially if, as a result of this design philosophy, no ductility capacity is provided in the system. This implies that the nonlinear behavior of yielding systems, which limits the seismic forces induced in structures, is a highly desirable feature.

[0003] For yielding systems, the energy dissipated per cycle through hysteretic yielding (inelastic deformations) is generally associated with structural damage. Such yielding systems are expected to sustain residual deformations which can greatly impair the structure and increase repair costs.

This raises important questions which usually remain unanswered following extreme loading conditions: does a structure that has undergone a certain level of inelastic deformation still provide the same level of protection as before? Must all yielded elements be replaced? Must the state of the material at every location where yielding has taken place be assessed?

[0004] There also exists a strong belief, mainly from the public, that a structure designed according to the latest seismic codes, for example, would require little or no structural repair and would result in minimal disruption time following an earthquake. Current research efforts in earthquake engineering still embrace this philosophy of achieving stable hysteretic response of predetermined elements of the structure. Structural damage and residual deformations are therefore expected under design level earthquakes.

[0005] For example, traditional steel braced frames are designed primarily to assure life safety under a major earthquake. They are expected to sustain significant damage after an earthquake due to repeated cycles of brace tension yielding and brace compression buckling. Furthermore, as a direct consequence of the damage induced in these elements, the final state of the entire building is likely to be out of plumb. Similar response is also expected from the other conventional steel, reinforced concrete, masonry and timber structural systems (moment-resisting frames, walls, etc.). Poor structural performance also results in damage to operational and functional components of buildings, such as architectural components, building services or building contents. Both structural and non structural damage can impact on the safety and rescue of building occupants and can lead to interruption of building operations.

[0006] This reality has important consequences as to the costs of repair and the costs induced by disruption time following an important

earthquake. Note that a structure that is found to be structurally sound after an earthquake may be condemned if the costs of straightening are elevated or if it appears unsafe to occupants. Increasingly, owners of structures in seismic prone areas that are faced with the expected state of their structure following a major earthquake often opt to directly implement higher performance systems. Furthermore, insurance companies are also increasingly basing their premiums on expected damage costs, and with this additional incentive, the number of owners that will adopt high performance systems for new or existing structures is likely to increase.

[0007] The current state-of-the-art for specialized dampers that are used to improve seismic performance mainly consists of either hysteretic (yielding), friction, viscously damped, viscoelastic systems or shape memory alloys. The hysteretic (yielding) systems consist of elements that are designed to undergo repeated inelastic deformations and that exhibit variable hysteretic responses.

[0008] A first family of such systems is referred to as yielding systems such as the buckling restrained braces or yielding steel plates. Yielding systems have been successfully implemented in numerous projects in Asia and North America. A second family of such systems is referred to as friction systems, of which one of the most popular is the Pall system. This system has been implemented in a very large number of structures in the past 15 years.

[0009] Note that none of these two families of systems exhibits self-centering properties, which can negatively impact on the overall performance of structures when subjected to earthquakes and other severe or extreme loads and may result in permanent deformations.

[0010] Viscous systems are specialized devices that exhibit a velocity dependent force and increase the damping of the structure thus reducing the response under seismic loading. Viscoelastic dampers also exhibit a velocity dependant force to increase damping while providing an additional elastic restoring force in parallel. Structures equipped with viscous and visco-elastic dampers require the main structural system to provide sufficient elastic stiffness and strength to resist the applied loads. These devices do not assure self-centering properties if the main structural elements undergo inelastic deformations.

[0011] A shape memory alloy is generally a metal that regains by itself its original geometrical configuration after being deformed or heated to a specific temperature. Shape memory alloys generally provide highly specialized production capability, but are generally expensive materials.

[0012] To date, self-centering behavior has mainly been achieved by specialized dampers comprised of complex inter-connected spring elements that require sophisticated fabrication processes and shape memory alloy materials that are prohibitive in most common structural projects because of elevated costs.

[0013] In US patent 5,819,484 entitled "Building structure with friction based supplementary damping in its bracing system for dissipating seismic energy" (issued on October 13, 1998), Kar teaches about a brace apparatus that provides re-centering capabilities through a friction spring energy dissipating unit, but which converts tension and compression applied to the apparatus into compression exerted on the stack between the two ends of the apparatus which are mountable to two portions of a building.

[0014] In US Patent No. 5,842,312 entitled "Hysteritic damping

apparati and methods" (issued on December 1st, 1998), Krumme et al. teach about damping apparatus using one or more tension elements fabricated from shape-memory alloy to provide energy dissipation. However, the apparatus of Krumme et al. which has two relatively moving bracing members linked together by the tension elements provides that some tension elements are involved during a force loading, but the self-centering behavior of the damping apparatus results from specific nonlinear material properties and do not involve mechanical interaction between elastic components.

[0015] The previous discussion leads to suggest that an optimal extreme load resistant system should:

[0016] i) incorporate the nonlinear characteristics of yielding structures to limit the forces imposed on the system by the severe or extreme loading, and dissipate input energy to control deformation;

[0017] ii) reduce the cost of repairs of the structure by encompassing re-centering properties allowing it to return to its original position after the extreme loading;

[0018] iii) further reduce the cost of repair by minimizing the occurrences of damages to the main structural elements.

[0019] Optimal resistance to severe or extreme loading increases the performance level of structures in the event of a major earthquake, hurricane or the like which sometimes occur in highly populated urban areas. Structures equipped with these high performance elements significantly offer better responses to such extreme loading with minimal damage, reduced repair costs and disruption time.

[0020] Furthermore, these systems may be very attractive to local, provincial and federal government facilities as well as to owners and managers of critical facilities that must remain functional during and immediately after major or catastrophic events.

OBJECTS OF THE INVENTION

[0021] An object of the present invention is therefore to provide an apparatus which encompasses the same architectural features as current technology and the same response characteristics under service loads, but offers a highly enhanced response under severe cyclic loading which minimizes structural damage and efficiently provides self-centering characteristics.

[0022] A further object of the present invention is to provide an apparatus which efficiently develops the aforementioned hysteresis and self centering capacities by combining simple and structural elements and readily available materials such as, for example, structural steel and high-strength tensioning elements.

SUMMARY OF THE INVENTION

[0023] More specifically, in accordance with the present invention, there is provided an apparatus designed in the form of a bracing system that achieves a hysteretic behavior and self-centering properties by combining specialized components that can be built using readily available construction materials. In addition the apparatus may be provided with energy dissipating systems such as, but not limited to, friction surfaces, yielding sacrificial members, visco-elastic materials, viscous fluid dampers or shape memory alloys to provide the desired level of energy dissipation.

[0024] There is therefore provided a brace apparatus to be mounted between two portions of a structure subjected to a loading force to limit movements due to the loading force, the brace apparatus including a fixed portion having a first end to be mounted to a portion of the structure, the first end defining a first abutting surface and a second end defining a second abutting surface, the brace apparatus further including a movable portion having a first end to be mounted to a portion of the structure, the first end defining a first abutting surface and a second end defining a second abutting surface, the brace apparatus further including a tensionable assembly mounting the movable portion to the fixed portion so that a) the first movable portion abutting surface is in proximity of the second fixed portion abutting surface, and b) the first fixed portion abutting surface is in proximity of the second movable portion abutting surface, the tensionable assembly including a first abutting element in the proximity of the first end of the fixed portion and a second abutting element in the proximity of the first end of the movable portion; the first and second abutting elements being interconnected by an adjustable tensioning element; wherein, i) when a loading force moves the movable portion away from the fixed portion, the first abutting element abuts the first fixed portion abutting surface and the second abutting element abuts the first movable element abutting surface to thereby limit the movement of the movable portion away from the fixed portion and ii) when a loading force moves the movable portion towards the fixed portion, the first abutting element abuts the second movable portion abutting surface and the second abutting element abuts the second fixed element abutting surface to thereby limit the movement of the movable portion towards the fixed portion.

[0025] There is therefore provided a brace apparatus mountable between two portions of a structure subjected to a loading force, the brace apparatus including a first bracing member having a first end mountable to one of the two portions and a second end, each having an abutting surface, a

second bracing member having a third end and a fourth end mountable to another one of the two portions and each having an abutting surface, the first and second bracing members being movably operatable between a rest position and a transitional position such that i) the first end is in proximity of the third end so as to define a first proximity end pair and the second end is in proximity of the fourth end so as to define a second proximity end pair, ii) the first end is opposed to the fourth end so as to define a first opposed end pair and the second end is opposed to the third end so as to define a second opposed end pair, the brace apparatus further including a tensionable assembly including abutting elements in the proximity of the first and second proximity end pairs, the abutting elements being interconnected by a tensioning element; whereby the first and second bracing members are movable apart when the loading force applied to the first opposed end pairs i) tensions the apparatus such that respective abutting surfaces of the first opposed end pair abuts on respective abutting elements, ii) compresses the apparatus such that respective abutting surfaces of the second opposed end pair abuts on respective abutting elements; the tensioning element being tensionable under the loading force such as to alternatively move the first and second bracing members from the rest position to the transitional position.

[0026] Other objects, advantages and features of the present invention will become more apparent upon reading of the following non-restrictive description of preferred illustrative embodiments thereof, given by way of example only with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] In the appended drawings:

[0028] Figure 1 is a side elevation view showing the interior of a brace apparatus according to a first illustrative embodiment of the present invention;

[0029] Figure 2 is a section view taken along line 2 in Figure 1;

[0030] Figure 3 is a section view taken along line 3 in Figure 1;

[0031] Figure 4a is an exploded partial side elevation view showing bracing members of the brace apparatus of Figure 1;

[0032] Figure 4b is an exploded partial side elevation view showing a tensionable assembly of the brace apparatus of Figure 1;

[0033] Figure 4c is a side elevation view showing the brace apparatus of Figure 4a subjected to a tension load;

[0034] Figure 4d is a side elevation view showing the brace apparatus of Figure 4a subjected to a compression load;

[0035] Figure 5 is a schematic view showing five possible energy dissipative systems which may be used in the brace apparatus of Figure 1;

[0036] Figure 6 is a schematic view showing individual hysteretic responses of dissipative mechanisms which may be used in the brace apparatus of Figure 1;

[0037] Figure 7 is a schematic view showing combined hysteretic responses of dissipative mechanisms which may be used in the brace

apparatus of Figure 1;

[0038] Figure 8 is a diagram view showing a typical hysteretic response for a yielding system;

[0039] Figure 9 is a diagram view showing a typical hysteretic response for a self-centering system;

[0040] Figure 10a is a schematic view showing the brace apparatus of Figure 1, equipped with a friction or yielding energy dissipative mechanism, when under tension and before the tension force is large enough to overcome the initial pre-tensioning of the tensioning elements;

[0041] Figure 10b is a diagram of the hysteretic response of the system as shown in Figure 10a;

[0042] Figure 10c is a schematic view showing the brace apparatus of Figure 1 equipped with a friction or yielding energy dissipative mechanism, when under tension and when the tension force is larger than the force required to overcome the initial pre-tensioning of the tensioning elements;

[0043] Figure 10d is a diagram of the hysteretic response of the system as shown in Figure 10c;

[0044] Figure 11a is a schematic view showing the brace apparatus of Figure 1 equipped with a friction or yielding energy dissipative mechanism, when under compression, and before the applied load is large enough to overcome the initial pre-tensioning of the tensioning elements;

[0045] Figure 11b is a diagram of the hysteretic response of the system as shown in Figure 11a;

[0046] Figure 11c is a schematic view showing the deformation of the different components of the brace apparatus of Figure 1 equipped with a friction or yielding energy dissipative mechanism when under compression and when the applied load is large enough to overcome the initial pre-tensioning of the tensioning elements;

[0047] Figure 11d is a diagram of the hysteretic response of the system as shown in Figure 11c;

[0048] Figure 12a is a schematic view showing the deformation of the different components of the brace apparatus of Figure 1 equipped with a viscous or visco-elastic energy dissipative mechanism when under tension and before the applied load is large enough to overcome the initial pre-tensioning of the tensioning elements;

[0049] Figure 12b is a diagram of the hysteretic response of the system as shown in Figure 12a;

[0050] Figure 12c is a schematic view showing the deformation of the different components of the brace apparatus of Figure 1 equipped with a viscous or visco-elastic energy dissipative mechanism when under tension and when the applied load is large enough to overcome the initial pre-tensioning of the tensioning elements;

[0051] Figure 12d is a diagram of the hysteretic response of the system as shown in Figure 12c;

[0052] Figure 13a is a schematic view showing the deformation of the different components of the brace apparatus of Figure 1 equipped with a viscous or visco-elastic energy dissipative mechanism when under compression and before the applied load is large enough to overcome the initial pre-tensioning of the tensioning elements;

[0053] Figure 13b is a diagram of the hysteretic response of the system as shown in Figure 13a;

[0054] Figure 13c is a schematic view showing the deformation of the different components of the brace apparatus of Figure 1 equipped with a viscous or visco-elastic energy dissipative mechanism when under compression and when the applied load is large enough to overcome the initial pre-tensioning of the tensioning elements;

[0055] Figure 13d is a diagram of the hysteretic response of the system as shown in Figure 13c;

[0056] Figure 14a is a schematic side elevation view of a first structure incorporating the brace apparatus of Figure 1;

[0057] Figure 14b is a schematic side elevation view of a second structure incorporating the brace apparatus of Figure 1;

[0058] Figure 14c is a schematic side elevation view of a third structure incorporating the brace apparatus of Figure 1;

[0059] Figure 14d is a schematic side elevation view of a fourth structure incorporating the brace apparatus of Figure 1;

[0060] Figure 14e is a schematic side elevation view of a fifth structure incorporating the brace apparatus of Figure 1;

[0061] Figure 14f is a schematic side elevation view of a sixth structure incorporating the brace apparatus of Figure 1;

[0062] Figure 14g is a schematic side elevation view of a seventh structure incorporating the brace apparatus of Figure 1;

[0063] Figure 14h is a schematic side elevation view of an eighth structure incorporating the brace apparatus of Figure 1;

[0064] Figure 14i is a schematic side elevation view of a ninth structure incorporating the brace apparatus of Figure 1;

[0065] Figure 14j is a schematic side elevation view of a tenth structure incorporating the brace apparatus of Figure 1;

[0066] Figure 15 is a side elevation view of a brace apparatus according to a second illustrative embodiment of the present invention;

[0067] Figure 16 is a top view of the brace apparatus of Figure 15;

[0068] Figure 17 is a section view taken along line 17-17 in Figure 15;

[0069] Figure 18 is a section view taken along line 18-18 in Figure 16;

[0070] Figure 19 is a side elevation view showing a first bracing member of the brace apparatus of Figure 15;

[0071] Figure 20 is a top view of the first bracing member of Figure 19;

[0072] Figure 21 is a side elevation view showing a second bracing member of the brace apparatus of Figure 15;

[0073] Figure 22 is a top view of the second bracing member of Figure 21;

[0074] Figure 23 is a top view of a brace apparatus according to a third illustrative embodiment of the present invention;

[0075] Figure 24 is a top view of brace apparatus according to a fourth illustrative embodiment of the present invention;

[0076] Figure 25 is a top view of brace apparatus according to a fifth illustrative embodiment of the present invention; and

[0077] Figure 26 is a cross-sectional view taken along line 26-26 in Figure 25.

DETAILED DESCRIPTION

[0078] The present invention relates to a brace apparatus provided for the dissipation of input energy applied to structure systems, such as for example beams, columns, braces, walls, wall partitions, subjected to severe,

extreme and/or repetitive loading conditions. The brace apparatus is mountable to portions of the structure to restrain or oppose to the relative motion between the two portions. In doing so, the brace apparatus generally maintains minimal residual deformations, dissipates energy and includes self-centering capacities once the input energy changes or ceases to be applied to the structure. Typically, input energies are related to exceptional loadings caused by winds, earthquakes, impacts or explosions which are sometimes imposed on structures or architectural systems.

[0079] As shown in the illustrative embodiment of Figure 1, the apparatus 30 generally includes a first bracing member 32, a second bracing member 34, a tensionable assembly 36, energy dissipative systems 38 and guiding elements 39. The second bracing member 34 may be viewed as a fixed member and the first bracing member 32 may be viewed as a movable member of the apparatus 30. Of course, one skilled in the art will understand that the movement between the members 32 and 34 is relative.

[0080] The bracing members 32 and 34, shown in Figures 1 to 3 and in more details in Figure 4a, include ends 40a, 40b, 40c, 40d provided with respective abutting surfaces 42a, 42b, 42c, 42d which are configured and sized as to abut with the tensionable assembly 36. The bracing members 32 and 34 further include apertures 45 providing the space requirement for the installment of the energy dissipative systems 38 and for inspection of the apparatus 30 after operation, as will be further described hereinbelow.

[0081] For clarity purposes, the various ends 40a, 40b, 40c, 40d of the bracing members 32 and 34 will also be referred to as "end pairs" of the apparatus 30 in the following description. More specifically, the end 40a which is in proximity of the end 40c define a first proximity end pair and the end 40b which is in proximity of the end 40d define a second proximity end pair.

Similarly, the end 40a which is opposed to the end 40d define a first opposed end pair and the end 40b which is opposed to the end 40c define a second opposed end pair.

[0082] In the illustrative embodiment of Figures 1 to 4d, ends 40a, 40d (the first opposed end pair) are further provided with end connections 44a, 44d adapted for mounting the apparatus 30 on the external structure (not shown) subjected to input energy. The end connections 44a, 44d are plates or any other structural element fixedly attached (welds, bolted or joined assemblies) to the bracing members 32 and 34. The end connections 44a, 44d are configured and sized so as to receive a loading force and as to transmit it to the apparatus 30. Optionally, the end connections 44a, 44d are further designed to yield at a certain loading force level to protect the integrity of the apparatus 30.

[0083] The bracing members 32 and 34, are generally parallel, longitudinally extending and independently movable one with respect to the other when subjected to a certain level of loading force. In the illustrative embodiment, the first bracing member 32 is a tubular member located inside of and generally concentric to the second bracing member 34.

[0084] As illustrated in Figures 1 to 3 and in more details in Figure 4b, the tensionable assembly 36 includes four adjustable tensioning elements 46 (only two shown in Figure 4b), and two abutting elements 48a, 48b interconnected by the tensioning elements 46. The tensioning elements 46 are generally pre-tensionable tendons, cables or rods which are mounted to the abutting elements 48a, 48b through various types of fastener assemblies, such as for example nuts 49, clamping or attachment devices capable of providing tension adjustability to the tensioning elements 46.

[0085] The tensioning elements 46 are generally symmetrically positioned with respect to the abutting elements 48a, 48b in order to provide for better load distribution within the tensionable assembly 36. The number of tensioning elements 46, their modulus of elasticity, their ultimate elongation capacity, their total area and their length are selected to achieve the desired strength, the post-elastic stiffness, the deformation capacity, and the self-centering capacity of the apparatus 30.

[0086] The tensioning elements 46 are capable of deforming under a loading force applied to the apparatus 30 such as to allow a targeted elongation of the apparatus 30 resulting from relative movement between the two bracing members 32 and 34, as will be further described hereinbelow. This deformation first generally occurs without yielding and with minimal loss of the pre-tensioning force in the tensioning elements 46.

[0087] The level of pre-tension in the tensioning elements 46 generally ranges from no pre-tension at all to some fraction, typically between 20% and 60% of the maximum allowed deformation of the tensioning element 46. The level of pre-tensioning determines the force level at which the relative movement starts between the bracing members 32 and 34, determines the initiation of energy dissipation in the energy dissipative mechanisms 38 and determines the change in the stiffness of the tensioning elements 46 ranging from the initial elastic stiffness to the post-elastic stiffness. The level of pre-tension also provides the re-centering capability of the apparatus 30, as will be further explained hereinbelow. If the level of pre-tension is not sufficient to overcome the force required to activate the energy dissipation mechanisms 38, the apparatus generally does not display a full re-centering capacity, but the tensioning elements 46 generally provide additional post-elastic stiffness to the apparatus 30.

[0088] The abutting elements 48a, 48b are plates or any other suitable structural elements that are positioned in the proximity of the first and second proximity end pairs 40a, 40c and 40b, 40d. The abutting elements 48a, 48b are configured and sized so as to cooperate with the abutting surfaces 42a, 42b, 42c, 42d of the ends 40a, 40b, 40c, 40d when the bracing members 32 and 34 are moving with respect to one another under a loading force, as will be further explained hereinbelow.

[0089] In the illustrative embodiment of Figures 1 and 4b, the abutting element 48a includes a passage (not shown) extending therethrough and into which the end connection 44a is slidably received. The other abutting element 48b is slidably received within the end connection 44d.

[0090] Turning back to Figures 1 and 3, the guiding elements 39 are shown in the form of plates, blocks, or other suitable structural elements which are provided between the bracing members 32 and 34 to allow, guide or impose the relative movement of the bracing members 32 and 34, while still helping to maintain their relative alignment. Guiding elements 39 may also be used to connect or mount the tensionable assembly 36 along the length of the bracing members 32 and 34, to enhance the buckling capacity of members 32 and 34. The guiding elements 39 may further include absorbing materials such as for example rubber, Teflon® or elastomeric materials which are used to mitigate impact between the bracing members 32 and 34.

[0091] Energy dissipative systems 38, which are schematically illustrated in Figures 1 to 5 and 10a to 13d, include friction 50, yielding 52, viscous 54 and/or visco-elastic 56 mechanisms or other components such as for example shape-memory alloys 57 that are mobilized or involved to dissipate energy when relative movement develops between the bracing members 32 and 34. These mechanisms may be used individually or in combination such

that the properties of the energy dissipative system 38 can be tuned to achieve any desired response under specific types of loading force. The energy dissipative system 38 is generally chosen to sustain minimal damage under severe loading and/or to be easily replaceable. Further, the energy dissipative system 38 is generally designed to allow quick inspection and replacement within the apparatus 30, with minimized disruption time following any extreme loading situation.

[0092] The friction mechanisms 50 illustrated in Figures 1 and 2 each includes two support members 60a, 60b, two friction interfaces 62a, 62b and an extending member 64. In the illustrative embodiment, the support members 60a, 60b are fixedly mounted on the bracing member 34, and each includes a slot 66. The extending member 64 is fixedly mounted on the bracing member 32 and extends toward the support members 60a, 60b such that fasteners 68 fixedly mounted through the extending member 64 engage the slots 66 to hold the friction mechanism 50 in a clamping arrangement.

[0093] The friction interfaces 62a, 62b are located in the clamping arrangement between the support members 60a, 60b and the extending member 64 are so configured and sized as to provide friction between the two bracing members 32 and 34. Depending on where friction sliding occurs in the friction mechanism 50, the friction interfaces 62a and 62b may or may not include slots that correspond to the slots 66 of the support members 60a, 60b.

[0094] The clamping arrangement provides that a normal force generates friction between the friction interfaces 62a, 62b when there is relative motion between the bracing members 32 and 34. In the illustrative embodiment of Figures 1 and 2, the slot 66 and fastener 68 are mounted in a sliding arrangement to first allow a relative movement between the bracing members 32 and 34. The sliding arrangement provides a restrained movement capacity

of the extending member 64 attached to the fastener 68, which is guided by the slot 66 along the direction of movement of the bracing members 32 and 34.

[0095] Optionally, the friction interfaces 62a, 62b may be removed from the friction mechanism 50 if support members 60a, 60b, and extending element 64 exhibit the required frictional characteristics. In this case, the friction is achieved by directly clamping together the support members 60a, 60b and the extending member 64. Further optionally, the slot 66 may be positioned directly on the extending member 64.

[0096] The friction mechanism 50 generally displays stable hysteretic characteristics under dynamic loading, with minimal uncertainty on initial and long-term friction properties. Specialized, non-metallic friction interfaces (not shown), or treated metallic surfaces (not shown) may also be used to provide specific hysteretic characteristics to the friction dissipative mechanism.

[0097] The yielding mechanisms 52, which are schematically shown Figure 5, may further be used as part of the energy dissipative system 38 to provide energy dissipative capacity when the two bracing members 32 and 34 are relatively moving. The yielding mechanism 52 includes metallic elements (not shown) inserted between and mounted to the two movable bracing members 32 and 34. The metallic elements (not shown) are generally selected to yield under axial, shear or flexural deformations, or a combination thereof.

[0098] The viscous mechanisms 54 and the visco-elastic mechanisms 56, which are schematically shown in Figure 5, may also further be used as part of the energy dissipative system 38 to provide energy dissipative capacity when the two bracing members 32 and 34 are relatively moving. The viscous mechanism 54 includes viscous devices (not shown)

containing viscous fluids (not shown) inserted between and mounted to the two movable bracing members 32 and 34. The viscous mechanism 54 includes visco-elastic materials (not shown) connected to plates inserted between and mounted to the two movable bracing members 32 and 34.

[0099] Combinations of more than one of the above mentioned mechanism 50, 52, 54, 56, 57 may then be used to optimize and diversify the hysteretic characteristics of the apparatus 30. With the addition of the tensionable assembly 36, the apparatus 30 is therefore able to exhibit a "Flag-Shaped Hysteresis" behavior, which combines energy dissipative and self-centering capabilities.

[0100] Figure 6 shows the individual contributions of the friction, yielding, viscous (at high and low velocity) and visco-elastic (at high and low velocity) mechanisms in terms of their force/deformation behavior. Figure 7 illustrates some combinations of those mechanisms.

[0101] Even if only two different dissipative elements are shown in Figure 7, a combination of more than two dissipative systems of the same type, or combinations of more than two types of dissipative mechanisms may also be used. Other combinations may also exist, such as for example, three different dissipative systems or more than one energy dissipative mechanism of the same type used in combination with another different energy dissipative mechanism. The overall hysteretic response of the apparatus 30 is generally obtained by summing the contributions from the various components described herein.

[0102] Figure 8 shows a force displacement curve of a typical linear elastic system and Figure 9 illustrates a typical self-centering system, both systems representing a yielding structure of equal initial stiffness and mass. In

these Figures, the shaded area represents the energy dissipated per cycle through hysteretic yielding, which is generally associated with structural damage to a structure under loading and which can significantly impair a structure and increase its repair costs. The self-centering capacity incorporated in the apparatus 30 offers a hysteretic behavior which is optimized (diagrammatically shown in Figure 9) having regards to the response and the residual deformation.

[0103] The apparatus 30 in operation is shown in Figures 4c and 4d and schematically illustrated in Figures 10a to 13d. These Figures illustrate the behavior of the brace apparatus 30, at the moment where input energy applied to the structure where the apparatus 30 is mounted to, is transmitted to the apparatus as loading forces, such as for example compression or tension forces. As stated hereinabove, the brace apparatus 30 is mountable to such structures via end connections 44a, 44d of the first opposed end pair 40a, 40d. The apparatus 30 is therefore able to receive the loading force such that its configuration changes from a rest position (Figure 1) to a transitional position where input energy is dissipated by relative motion between the two structural bracing members 32 and 34 (Figures 4c, 4d).

[0104] As shown in Figure 4c when under a certain level of tension loading force, the brace apparatus 30 allows for a relative movement of the bracing members 32 and 34. First the pre-tensioning of the tension elements 46 has to be overcome, which then results in the elongation of the tensioning elements 46 and the initiation of relative movement between the bracing members 32 and 34. In the process, the tensioning elements 46 are further tensioned since abutting surface 42a pushes on abutting element 48a and since abutting surface 42d pushes on abutting element 48b. When under a compression force, as illustrated in Figure 4d, the tensioning elements 46 of the tensionable assembly 36 are also further tensioned in the process, since

abutting surface 42c pushes on abutting element 48a and since abutting surface 42b pushes on abutting element 48b.

[0105] By elongating, an additional tension force gradually builds-in the tensioning elements 46 such as to provide the self-centering properties of the brace apparatus 30. For instance, if the loading force was to cease at that time, the apparatus 30 is generally brought back to its rest position (see Figure 1) by the additional tension force developed in the tensioning element 46. As stated previously, if the level of pre-tension is not sufficient to overcome the force required to activate the energy dissipation mechanisms 38, the apparatus generally does not display a full re-centering capacity, but the tensioning elements 46 generally provide additional post-elastic stiffness to the apparatus 30.

[0106] As soon as relative motion between the bracing members 32 and 34 starts to occur under the loading force, the energy dissipative system 38 (only friction mechanism 50 shown in Figures 4c, 4d) are activated, opposing to the relative motion of the bracing members 32 and 34. For instance, when tension is applied to the apparatus 30 as in Figure 4c, and once the initial force and resistance of the tensioning elements 46 are overcome, the apparatus 30 elongates while energy is dissipated through the dissipative system 38. As discussed previously, the illustrative embodiment of Figure 4c shows that the fasteners 68 in a sliding arrangement with the slot 66 generally move along the relative direction of movement of the bracing members 32 and 34.

[0107] At that time, depending on the selected tensioning elements 46 with respect to the resistance and configuration of the selected combination of energy dissipative systems 38, the additional tension force developed in the further extended tensioning elements 46 generally provides to the apparatus 30 the capacity of heading back to its initial position (Figure 1) when the loading

force ceases or changes from tension to compression.

[0108] Another example highlighting the hysteretic behavior of the apparatus 30 while in operation is schematically illustrated in Figures 10a to 13d. More specifically, Figures 10a to 11d illustrate the hysteretic behavior of a brace apparatus 30 submitted to tension and compression and equipped with a friction mechanism 50 or with a yielding mechanism 52. In Figures 12a to 13d illustrate the hysteretic behavior of the apparatus 30 submitted to tension and compression and equipped with velocity dependant viscous mechanism 54 or visco-elastic mechanism 56.

[0109] In all these figures, the elongation of the apparatus 30 under the loading force F is expressed as δ, while δ' illustrates the deformation in the mechanisms 50, 52, 54, 56 mounted to the two bracing members 32 and 34. In Figures 12a to 13d, both a low velocity and high velocity response are illustrated since this energy dissipative system displays a velocity dependent hysteresis. The high velocity response is generally expected during the extreme loading, while the low velocity response (which generally provides the self-centering property) characterizes the expected response following the extreme loading.

[0110] For concision purposes, the relative movements involved during operation of the brace apparatus 30 subjected to loading forces will be further explained with reference to Figures 10a to 11d only, but the same principles apply to other combinations of different energy dissipative system (Figures 12a to 13d) as described hereinabove.

[0111] Figure 10a schematically illustrates the brace apparatus 30 equipped with a friction mechanism 50 or yielding mechanism 52 mounted to the bracing members 32 and 34 and subjected to a tension loading force, but

before the applied tension loading force is large enough to overcome the initial pre-tensioning of the tensioning element 46.

[0112] Up to a certain level, a force F tensions the apparatus 30 such that the tensioning element 46 and the dissipative mechanism 50, 52 opposes to the relative motion of the bracing members 32 and 34. At that stage, the apparatus 30 generally starts to linearly deform as schematically illustrated in Figure 10b.

[0113] If the loading Force F reaches a certain level which is larger than the force required for overcoming the initial pre-tensioning of the tensioning element 46, the force F reaches the tension separation level (70 in Figures 10b and 10d). At that time, the members 32 and 34 start moving in opposite directions by a distance δ, as schematically illustrated in Figure 10c. The stiffness then changes from the elastic to the post-elastic stiffness. The tensioning element 46 mounted to both members 32 and 34 is therefore elongated by a generally similar displacement and may deform under such loading. The dissipative mechanism 50, 52 generally also deforms by a displacement δ'.

[0114] Once the loading force changes its direction such as it usually does in an oscillatory earthquake loading, the opposite compression force F shown in Figure 11a moves the bracing members 32 and 34 toward their original position, which generally corresponds to an opposite and equal displacement δ. At this stage, the two bracing members 32 and 34 are generally aligned and the dissipative mechanism 50, 52 generally put back to its initial configuration. If no compression force F is provided after the tension loading F, the additional tension force built in the tensioning element 46 generally repositions the bracing members 32 and 34 to the configuration shown in Figure 11a. As explained hereinbefore, this phenomenon may be

explained by the pre-tensioned and further stretched condition of the tensioning element 46.

[0115] As seen in Figure 11b, the corresponding hysteretic response of the dissipative mechanism 50, 52 moves from the tensioned side of the force F toward the compression side of the force F by passing generally near the zero force-displacement point in the diagram. In the case where no opposite compressive force F is provided, the additional tension force of the tensioning element 46 returns the system to the rest position, generally corresponding to the zero force-displacement point in the diagram.

[0116] When the opposite force F reaches a compression separation level 72 required for overcoming the initial pre-tensioning of the tensioning element 46, as illustrated in Figure 11d, the dissipative mechanism 50, 52 and the tensioning element 46 are overcome such that the bracing members 32 and 34 start moving in opposite directions by a distance δ. The dissipative mechanisms 50,52 then generally deform by a corresponding displacement δ'.

[0117] Generally speaking, the relative movements of the various components of the apparatus 30 described hereinabove may alternate as long as the deformation imposed on the apparatus 30 remains within the maximum deformation for which the apparatus 30 has been sized for. As described hereinbelow in other illustrative embodiments, the bracing members 32 and 34 may include specially designed end connections 44a and 44d, or an additional structural element generally mounted in series to the apparatus 30, that may be designed to yield or slip with friction prior to attaining the ultimate deformation capacity of the tensioning elements 46, and thus minimizes the possibilities of the tensioning elements 46 failing in the event of unexpectedly higher deformations caused by energy input level higher than anticipated and thus protect the integrity of the apparatus 30.

[0118] The bracing members 32 and 34 are typically made out of any material generally used for rigid structures or architectural constructions, such as, for example, steel, aluminum or fiber reinforced polymers (FRP). The material of the members 32 and 34 is generally chosen to prevent or minimize the buckling or yielding occurrences and, thereby, to significantly reduce damages to the portions of the structure to where the members 32 and 34 are mounted. The tensioning elements 46 may also further be made from various types of materials such as for example tendons bars or cables which may be made of, but not limited to, high strength steel tendons, rods, bars or of composite FRP tendons or bars including, for example Aramid, Carbon, Glass or the like. The tensioning elements 46 may further be provided with a UV or fire protective layer.

[0119] The apparatus 30 which as been described herein may therefore be used by being mounted on, connected to or integrated in various types of structures 74, such as for example in, multi-storey structures, buildings, towers, bridges, offshore platforms, storage tanks, etc, some being shown in Figures 14a to 14j.

[0120] The apparatus 30 may further be used for new constructions which are built with traditional lateral load resisting systems (conventional braced frames, moment-resisting frames, shear walls, etc.) or with added dampers that do not exhibit the self-centering property. Structures may further be built with the apparatus 30 to enhance their seismic performance level, such structures including, for example, machine parts, buildings, bridges, towers, offshore marine structures, bridges or other structural applications (towers, chimneys. These structures may be subject to any type of loading, including acoustical, seismic, blast, impact wave and wind loading.

[0121] The apparatus 30 may still further be used with existing

constructions which need to be strengthened or rehabilitated to meet more recent (generally more stringent) seismic code provisions or higher performance criteria. Rehabilitation of these structures could be done by using the proposed apparatus 30 for enhanced response under severe or extreme seismic or wind loading conditions. The apparatus 30 may also further be used in important structures which need to be protected from extreme blast loads. Furthermore, the apparatus 30 may also be used in other applications, such as for example, in mechanical engineering for vehicles subjected to impact, equipment or machinery that can be subjected to overloading or unanticipated loading conditions, etc.

[0122] The apparatus 30 is generally installed as a brace element between framing members in a structure, at an angle, vertically or horizontally at the base of structures, or generally in parallel with any movement within the structure that may necessitate control.

[0123] The fabrication of the apparatus 30, its inter-connections and its connections to existing structures generally involve steps which may be made by regular construction workers. The apparatus 30 is generally entirely self-contained. Once assembled in the production factory, the apparatus 30 is then generally readily attachable or mountable to the structures in a similar way as traditional bracing elements are generally attached, by bolting or welding of the end connections (44a, 44d in Figure 4a) to the main structure needing bracing.

[0124] The apparatus generally includes inspection provisions, such as for example in the form of holes (not shown) in the bracing members to provide for inspection of the energy dissipative mechanisms that undergo deformations and dissipate input energy under extreme or repetitive loading conditions. If needed, the energy dissipative mechanisms may be individually

replaceable from the inspection provisions following an extreme loading event.

[0125] A person skilled in the art will also easily understand that the number and the physical properties of tensioning elements may vary, and that the size, the shape, and numbers of bracing members may also vary. For instance, the bracing members may be made of circular, square or rectangular steel tubes or any combinations thereof. Other shapes can be used such as interconnected plates, I-shapes, C-shapes, etc. Further, other configurations and other types of energy dissipation systems may be used. More specifically, the friction mechanisms described may be located in a single location or in two or more locations, at any position along the length of the brace apparatus.

[0126] A brace apparatus 130 according to a second embodiment of the invention is illustrated in Figures 15 to 22. For concision purposes, only the differences between the brace apparatus 130 and the brace apparatus 30 illustrated in Figures 1 to 14j will be described hereinbelow. For simplification purposes, end connections (44a, 44d) will not be represented on Figures 15 to 22.

[0127] In this second illustrative embodiment, the brace apparatus 130 includes a first bracing member 132, a second bracing member 134, a tensionable assembly 136 and an energy dissipative system 138.

[0128] The energy dissipative system 138 includes two friction mechanisms 150a, 150b provided in proximity of the ends 140a, 140b, 140c, 140d. These friction mechanisms 150a, 150b each includes support members 160a, 160b, 160c, 160d mounted on the second bracing member 134 and extending members 164a, 164b mounted on the first bracing member 132. In this illustrative embodiment, the support members 160c, 160d and the extending member 164a further act as end connections for mounting the

apparatus 130 on external structures and transmitting the loading force to the apparatus 130.,

[0129] The extending members 164a, 164b each include slots 166a, 166b, 166c, 166d where fasteners 168 are received in, such as to clamp the extending members 164a 164b with the support members 160a, 160b, 160c, 160d. The slots 166a, 166b, 166c, 166d and fasteners 168 are mounted in a sliding arrangement to allow a restrained relative under friction movement between the bracing members 132, 134.

[0130] A person skilled in the art will easily understand that the energy dissipative mechanism illustrated in this embodiment may be replaced by another hereinabove presented energy dissipative mechanism, such as, for example, a yielding, viscous, visco-elastic, or hysteritic mechanism.

[0131] A brace apparatus 230 according to a third embodiment of the invention is illustrated in Figure 23. For concision purposes, only the differences between the brace apparatus 230 and the brace apparatus 30 illustrated in Figures 1 to 14j will be described hereinbelow.

[0132] In this illustrative embodiment, the brace apparatus 230 includes an inner bracing member 232, and two outer bracing members 234, 235 that are located on each side of the inner bracing member 232, a tensionable assembly 236, an energy dissipative system 238 and guiding elements 239.

[0133] The inner and outer bracing members 232, 234, 235 have ends 240a, 240b, 240c, 240d, 240e, 240f provided with respective abutting surfaces 242a, 242b, 242c, 242d, 242e, 242f. Ends 240a, 240d and 240f are

further provided with end connections 244a, 244d, 244f, which in this embodiment include a threaded portion 245a, 245d, 245f.

[0134] The tensionable assembly 236 includes abutting elements 248a, 248b interconnected by tensioning elements 246. The abutting elements 248a, 248b are in proximity of the ends 240a, 240b, 240c, 240d, 240e, 240f and the tensioning elements 246 are symmetrically positioned with respect to the inner and outer members 232, 234, 235 such as to favor a generally evenly distributed loading force in the tensionable assembly 236 and allow a generally uniform deformation of the apparatus 230 in operation. In this illustrative embodiment, the tensioning elements 246 are positioned outward of the outer members 234, 235.

[0135] The energy dissipative system 238 includes two friction mechanisms 250 that are each fixedly mounted to the inner bracing member 232, and which extend in a frictional connection with the outer bracing members 234, 235.

[0136] The guiding elements 239 are fixedly mounted to the each of the tensioning members 248a, 248b and mounted in a guiding cooperation with the ends 240b, 240c, 240e of the bracing members 232, 234, 235 which are not provided with an end connection 244a, 244d, 244f. The guiding elements 239 generally slidably restrain and guide the relative movement of the bracing members 232, 234, 235. Optionally, the guiding elements 239 are mountable outside 0f the bracing members 232, 234 and 235.

[0137] The brace apparatus 230 operates in a similar way as described in the first embodiment. However, the loading force applied to the outer bracing members 234, 235 is half the force applied to the inner bracing member 232, but the effective apparatus 230 elongation is the same since two

outer bracing members 234, 235 participate in elongating the apparatus 230.

[0138] A person skilled in the art will easily understand that the energy dissipative mechanism illustrated and described in this embodiment may be replaced by another hereinabove presented energy dissipative mechanism, such as, for example, a yielding, viscous, visco-elastic, or hysteritic mechanism.

[0139] A brace apparatus 330 according to a fourth embodiment of the invention is illustrated in Figure 24. For concision purposes, only the differences between the brace apparatus 330 and the brace apparatus 230 illustrated in Figure 23 will be described hereinbelow.

[0140] In this illustrative embodiment, the tensioning elements 346 of the tensionable assembly 336 are located inside the inner bracing member 332 and inward with respect to the outer bracing members 334, 335. Optionally, the tensioning elements 346 may be located inside the outer bracing members 334, 335.

[0141] A person skilled in the art will easily understand that the energy dissipative mechanism illustrated in this embodiment may be replaced by another hereinabove presented energy dissipative mechanism, such as, for example, a yielding, viscous, visco-elastic, or hysteritic mechanism.

[0142] A brace apparatus 430 according to a fifth embodiment of the invention is illustrated in Figures 25 and 26. For concision purposes, only the differences between the brace apparatus 430 and both the brace apparatus 30 illustrated in Figures 1 to 14j and the brace apparatus 130 illustrated in Figures 15 to 22 will be described hereinbelow.

[0143] The brace apparatus 430 is mounted to an external structure 431 at an attachment portion 431a. The brace apparatus 430 includes a first bracing member 432, a second bracing member 434, a tensionable assembly 436, a fuse system 437 and an energy dissipative system 438.

[0144] The energy dissipation system 438 includes a friction mechanism 450 which includes an extending member 464 with an end portion 465 protruding from the apparatus 430 such as to be mountable to the attachment portion 431a and thereby receive and transmit the loading force to the apparatus 430. In the illustrative embodiment, the end portion 465 includes four slots 467a, 467b, 467c, 467d configured and sized as to cooperate with the fuse system 437.

[0145] The fuse system 437 includes a slipping member 469 provided with a plurality of fasteners 471. The slipping member 469 includes connectors 473 so configured and sized as to cooperate with the attachment portion 431a.

[0146] The fasteners 471 are mounted in a sliding arrangement with the slots 467a, 467b, 467c, 467d to allow a restrained relative and under friction movement, which generally occurs at a predetermined load, between the apparatus 430 and the attachment portion 431a.

[0147] For instance, the slip load of the slipping member 469 with respect to the slipping portion 465 is adjustable to occur at a value corresponding to an acceptable maximum deformation value of the apparatus 430, such that once the slip of the slipping member 469 occurs, any additional deformation in the apparatus 430 occurs between the slipping member 469 and the slipping portion 465. At that time, no additional deformation is imposed on the tensioning elements 446.

[0148] To further provide that the deformation occurs between the slipping member 469 and the slipping portion 465 while minimizing the probability of overloading and damaging the apparatus 430, the deformation capacity of the energy dissipative system 438 may be limited to a pre-determined value preventing further relative movement to develop between the bracing members 432 and 434.

[0149] For instance, for a friction mechanism 450 as illustrated in this embodiment, the length of the slots 466a, 466b are adjustable such that when the acceptable deformation value is reached in the apparatus 430, the fasteners 468 of the friction mechanism 450 start bearing on the edges of the slots 466a, 466b thus opposing to any more relative deformation in the apparatus 430 and consequently, in the tensioning elements 446. It is generally at that time that any additional deformation occurs between the slipping member 469 and the slipping portion 465, as described hereinabove.

[0150] A person skilled in the art will easily understand that the fuse system 437 described in this embodiment may also be used by replacing the friction mechanism by another energy dissipative mechanism or other blocking systems to protect the apparatus in case of excessive deformation demand such as, for example, a yielding mechanism. Further, the fuse system described in this embodiment may further be used with any of the previously described embodiments and that the number of slots, the type and number of fasteners and connectors may vary according to the design requirements of the brace apparatus.

[0151] Although the present invention has been described hereinabove by way of preferred illustrative embodiments thereof, it can be modified, without departing from the spirit and nature of the subject invention as defined in the appended claims.